Indian Journal of Natural Sciences *www.tnsroindia.org.in ©IJONS*
Vol.9 /Issue 51 / December / 2018 *International Bimonthly* *ISSN: 0976 – 0997*

RESEARCH ARTICLE

Preliminary Neo-Deterministic Seismic Hazard Assessment in Pakistan and Adjoining Regions

Farhana Sarwar[1]*, Saleem Iqbal[1], Franco Vaccari[2], Andrea Magrin[3] and Lala Rukh[1]

[1]Department of Mathematics, University of Balochistan, Quetta, Pakistan.
[2] Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy
[3] Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Udine, Italy

Received: 22 Sep 2018 Revised: 25 Oct 2018 Accepted: 27 Nov 2018

***Address for Correspondence**
Farhana Sarwar
Department of Mathematics,
University of Balochistan,
Quetta, Pakistan.
Email: f_saleem10@yahoo.com

ABSTRACT

The regional seismic hazard in Pakistan and adjoining regions is assessed using the Neo-deterministic seismic hazard assessment approach (NDSHA). Synthetic seismograms are generated by the modal summation technique at the nodes of a grid that covers the studied area. The main input for the computations consists of a set of earthquake sources and of the structural model where the seismic waves propagate. The earthquake sources are parameterised within the active seismogenic areas by defining the focal mechanism, the depth and the magnitude, obtained through the analysis and re-elaboration of the past seismicity. The peak displacement (D_{max}), peak velocity (V_{max}) and design ground acceleration (DGA) are then extracted from the synthetic signals and plotted on the 0.2° x 0.2° grid to construct the seismic hazard map of the studied area. There are few probabilistic hazard maps available for Pakistan, however, this is the first study aimed at producing a neo-deterministic seismic hazard map for Pakistan and adjoining regions.The most severe hazard is found in the epicentral zone of the great Muzaffarabad earthquakes of 2005 and its surroundings, where the DGA estimate falls in the highest range 0.60 g – 1.2 g. The peak velocity and displacement in the same region are estimated as 60–120 $cm\ s^{-1}$ and 30–60 cm, respectively.

Keywords: Seismic hazard, Neo-deterministic, Earthquake catalogues, Seismogenic zones

INTRODUCTION

Pakistan is situated in a highly seismically active region which has experienced many disastrous earthquakes during historical as well as in recent times. The geographical map of Pakistan with adjoining regions considered in our studies is shown in Fig.1 .The strongest earthquakes that hit Pakistan in the recent history are the 1935 Quetta earthquake, M 7.4; the 1945 Makran coast earthquake, M above 8.0; the August 1931 Mach earthquake, M 7.3; the 1974 Pattan earthquake, M 6.0; the October 2005 Muzaffarabad earthquake, M 7.6[1], the 28 October 2008 Ziarat earthquake, M 6.4; the 24 September 2013 Awaran district (Balochistan) earthquake, M 7.8 and its September 28, 2013 M 6.8 aftershock. Given the high seismicity of the region, it has become necessary to better quantify the seismic hazard, to evaluate the rate of vulnerability and to develop tools to prevent or mitigate as much as possible the potential damaging effects of earthquakes. A reasonable approach is to apply the Neo-deterministic seismic hazard assessment (NDSHA) technique [2],[3]that can be effectively combined with intermediate term middle-range predictions [4], [5], [6], [7] at least to identify priorities of interventions for retrofitting and new urban planning. In recent times awareness has grown that people are usually not killed by earthquakes themselves but by their collapsing houses and other manmade structures or induced secondary effects. In many developed and industrialized countries,like Japan, protection from earthquakes, in conjunction with improved seismic hazard assessment, is entrusted chiefly to the broad application of advanced engineering know-how. But unfortunately,in developing countries like Pakistan the situation is different. Pakistan cannot yet afford excessive costof engineered earthquake-resistant buildings and still foresee potential applications of results of earthquakeprediction research for reducing human losses. However, earthquake losses could be significantly minimizedwith elementary design know how only, and by constructing rural housing at minimum cost by applying low-costtraditional measure of retrofitting, i.e., building materials and local skills. More emphasis should be givento pre-disaster planning and development and efforts must be put to cost effective prior actions focused atdeveloping knowledge-based hazard resilient public property, rather spending our time and resources on postdisaster relief and rescue operations that are not only expensive but difficult as well. Good understandingand know-how of the maximum credible earthquake that might occur, the threat to infra structures at thegiven site or zone, the geographical site effects and the dangers we confront, is essential for this sort ofscenario modelling and to achieve our purpose NDSHA is a more practical approach.

Seismic Hazard

Among the possible definitions of seismic hazard analysis, [9] describes it as the estimation of some measure of the strong earthquake ground motion expected to occur at a selected site. Approaches to seismic hazard assessment can be grouped into two broad categories: Deterministic (DSHA) and Probabilistic (PSHA)[10]. In both the approaches, available historical seismic records and geological data are used to identify and characterize the main seismic sources relevant to the site of interest, and to define the earthquake potential. The difference between these two methodologies lies in the way the seismic scenarios are defined. The PSHA defines the hazard as the likelihood for a specified ground motion parameter (e.g. peak ground acceleration, PGA) value to be exceeded within a certain time interval. The DSHA is defined by a controlling earthquake, an earthquake with a given magnitude that may occur in a given time interval (disastrous [say 500 years]; strong [say 140 years]; frequent [say 70 years]; etc.), without given an indication on how likely that given scenario is to occur [4].

The Neo-Deterministic Seismic Hazard Assessment (NDSHA)

In DSHA all distances from the sites to the potential earthquake sources, as well as the magnitudes of the earthquakes within the potential sources, are fixed [10]. The result is an estimate of the ground motion that the site would experience given the occurrence of an earthquake at some fixed distance and magnitude. Deterministic seismic hazard analyses are useful for site-specific studies, particularly those involving critical facilities in which the design criteria are based upon the occurrence of the largest possible seismic event [4],[10]. The deterministic approach is also preferable in view of the limited seismological data availability and of the intrinsic difficulty of the probabilistic evaluation of the occurrence of earthquakes. As explained by the multiscale seismicity model [11], the actual problem is the selection of large enough dimensions of the areafor analysis without violating the Gutenberg-Richter as well as other related laws.

NDSHA, being based on the computation of a large set of synthetic seismograms, addresses some aspects largely overlooked in the probabilistic approach: (a) the effect of crustal properties on attenuation are not ignored; (b) the ground motion parameters are not derived from overly basic attenuation functions, but from synthetic time histories,and (c) the resulting maps address the issue of the deterministic definition of ground motion in a way which permits the generalisation of design parameters to locations where there is little seismic history [12], [13]. Various studies have been performed in the past to evaluate PSHA in Pakistan [e.g. [1], [14], [15]. The deterministic approach for seismic hazard analysis is not well documented in literature, and it is practiced differently in different parts of the world and even in different application areas [9].

MATERIALS AND METHODS

In this study, we compute the seismic hazard in the country using the NDSHA approach described in [2],[3], that allows for a first-order seismic zoning at regional scale, based on the knowledge of the average properties of seismic sources and structural models [16]. With NDSHA, the available information on the Earth structure parameters, the seismic sources and the level of seismicity of the area are used for the computation of synthetic seismograms, according to the flow chart shown in Fig. 2. Once estimated for the available data the synthetic seismograms permit us to calibrate in a quitepractical manner the engineering standards essential to appropriately design or retrofit the buildings, even in those areas that are seismically quiet, or where no proper data is available. In addition, the technique also permits to estimate the impact of several input factors on the concluding results. The immediate results of the technique are the maps exhibiting the distribution of the D_{max}, $V_{max}$and *DGA* for the studied area. The full description of the methodology is discussed in [17].

RESULTS AND DISCUSSIONS

Input Data

The input data needed to compute the synthetic seismograms are structural models, historical earthquakes catalogue, seismogenic zones and focal mechanisms.

Structural model

Structural models are defined by regional polygons (Fig. 3) that separate areas characterized by different average lithospheric properties; they are represented by a number of flat layers, each one described by its thickness, density, P- and S-wave velocities and corresponding Q values. The structural models and Q-Structure beneath the studied area has not been very well studied so far. In order to propose a suitable structural model, all available geophysical and geological information for the investigated territory have been considered after an extensive bibliographic research [18], [19], [20] [21], [22], [23], [24], [25], [26], [27], [28]. An average model is prepared giving more weight to the results obtained by [18]. For depths larger than 120 km the data has been taken exclusively from [18]. For each polygon an average structural model is prepared for our computation which is shown in Fig.4

Earthquake catalogue

An earthquake catalogue has been prepared after merging the Pakistan Metrological Department (PMD) catalogue and the National Earthquake Information Centre (NEIC) catalogue for a period of 102–years from 1905 to 2007 [29] and from Indian catalogue for a period of 01-01-500 to 30-12-2016 [30], [31]. In NDSHA completeness of catalogue is not as essential as in PSHA and is in principle required only for events of M=5 and above. Furthermore, only the spatial distribution of those events is considered, disregarding their time distribution, which is often unreliable for ancient events. We may be misjudging the seismicity just in those Seismogenic Zones wheredamaging events are not reported in the catalogue, and only in those areas where the magnitude smoothing, described in Section 3, is not enough to account for the missing information. This insufficient information would also influence significantlythe results obtained with PSHA[18], where catalogue completeness at lower magnitudes is also required for a good characterization of the seismicity rate.As given by [32], attainable partial solution to find maximum expected magnitude can be achieved through aimed field studies of active faults for the identification of the seismogenic potential.A formal approach to the identification of seismogenic nodes has been developed by [33]. About Pakistan, in 1972 [34] used planar morphostructural nodes of the Pamirs and Tien Shan as candidates for earthquake-prone places.

Seismogenic zones

Seismogenic zones identify the areas with the active faults of the region. Pakistan geologically overlaps both with the Indian and the Eurasian tectonic plates where its Sindh and Punjab provinces lie on the north-western corner of the Indian plate while Balochistan and most of the Khyber-Pakhtunkhwa lie within the Eurasian plate which mainly comprises the Iranian plateau, some parts of the Middle East and Central Asia. The Northern Areas and Kashmir lie mainly in Central Asia along the edge of the Indian plate and hence are prone to violent earthquakes where the two tectonic plates collide [35]. Seventeen seismogenic zones have been defined for the entirearea of research comprising of Pakistan and adjoining regions of Iran, Afghanistan, Tajikistan, China, India as shown in Fig. 5. They represent areas characterized by a significant level of seismicity. The stress regime and the tectonic behaviour are assumed to be reasonably homogeneous within each zone. Most of the seismogenic zones are located along the collision plate boundary, i.e., along the Kirthar Suleiman Hindukush, Himalaya[18]. Seismic activity has generally been concentrated in the northern part of the country, the northern and southwestern parts of Balochistan Province, and the coastal areas of Sindh Province. Khattri[36] identified twenty-four source zones in India and neighbouring region on the basis ofseismotectonics and historical seismicity but the region around the Killari earthquake of 1993 (Mw 6.3) was not recognized in his study. Bhatia[37] identified eighty-six source zones for India and adjoining regions, based on the analysis of past data, and the Killari source zone was among them. The identified areal sources were smaller in size compared to those of Khattri [36]. In our study we have followed the same pattern of zoning as given in [18] and owing to the same justification by [18] the zoning suggested by [36] and [37] is not adopted as the proper definition criteria for zoning is not been followed for the complete studied area. For instance [36] has formed twenty-five zones for the complete region but due to varying size of the zones as some are considerably big and so cannot be considered homogeneous in their properties. Similarly, there is not a single event assigned to seismogenic zone 1 of [37] whereas for zone 81 an earthquake of M 7 is lying just outside it. As could be seen that few source zones 70-75 are formed on the basis of low magnitude local events, whereas in other parts of the studied area similar size earthquakes are not considered in the definition of Seismogenic zones. As in [38] the India and its neighbouring regions are divided into "32" Seismogenic zones, that were established on historical seismicity, geology and tectonic features but there is no zone with zero seismic activity and Seismogenic zones without gaps but in our research, we are focused on events with $M \geq 5$ and focal depths <50 km.

Fault plane solutions

In this research we have taken published Fault Plane Solutions (FPS) for the large events occurring before 1976 from[39], [40], [41], [42], [43], [44], [45], [46], however from 1976 and onwards the FPS are taken from Harvard CMTCatalogue. Each seismogenic zone is assigned a representative fault plane solution based on the mechanism associated with the strongest event, or with the best studied event, or the most frequent event. The thrust-type and strike-slip fault plane solutions are dominating the region of investigation (Fig. 5). The Karakoram ranges mostly shows thrust fault mechanism due to the collision between Indian and Eurasian plate (zones 1and 2), Hunza and Gilgit valleys are situated in this zone.Generally, thrust faulting mechanism can be observed in the region of Hindu Kush (zones 3,4,14 and 15) occasionally normal faulting (zones 3 which comprise Main Karakoram Thrust MKT),also in Kashmir (zone 4) the earthquakes mainly shows thrust fault mechanism, zone 14 lies in the central Afghanistan which is seismically inactive. The zone- 5 comprises Kangra Valley fault (KVF) India, the mechanism is generally normal faulting while zone 6 and 7 shows thrust fault mechanism and consists of the Main Boundary Thrust **(**MBT) and represents the extensive zone of modern deformation and the devastating earthquakes. In Pakistan active faults are rather densely distributed on and in the vicinity of the MBT [35]. For zone 8 the CMT database do not have any focal mechanism solution, the solution has been taken from [18] which is vertical dip slip, the area lies in the region Rajasthan in India. In the zone 9,10 there are strike slip faults including Chaman fault, indicating that the boundary between Indian and Eurasian plate is of transform type. For zone 11, thrust as well as strike slip faults are dominating although no large earthquake is observed in this zone except 2011 earthquake [35], this zone has main cities namely Panjgur, Dalbandin, Nokundi and areas of Iran.The zone -12 and 17 has Kirthar fault with a relatively diffused seismicity. In the southern part of Pakistan, including Makran subduction zone(zone 13), faults are thrust and normal type due to the subduction of Arabian Sea plate under Eurasian plate and due to Murray ridge, we also observe that Nai-Rud fault is an active fault in this zone and has a NE-SW trending, almost parallel to the Nai-Rud valley and bears the characteristics of a thrust with left-lateral strike-slip component, the main cities in this region are Gawadar, Pasni, Karachi.Zone 16 shows reverse thrust mechanism and include Parts of Iran and boarder of Afghanistan.

Computations

For the definition of the seismic sources used to generate the synthetic seismograms, the seismicity described in the historical earthquake catalogue is discretised into cells of 0.2° × 0.2° (latitude and longitude) and each cell is assigned the magnitude value of the largest event that occurred within it (Fig. 6). This map of seismicity is then rearranged through a smoothing procedure to account for the spatial uncertainty in epicentres location that may be particularly severe for historical events [e.g. [33]] and for the source extension. A centredsmoothing window with a radius of three cells is considered, and the maximum value found in the window is assigned to the central cell. After smoothing, only the cells located within the seismogenic zones are retained, obtaining the conservative distribution of the maximum magnitude shown in Fig. 7.

A double-couple point source is then placed in the centre of each cell, with a focal mechanism consistent with the properties of the corresponding seismogenic zone. The observation points are placed at a grid with dimension of 0.2° × 0.2° over the whole studied area. They do not overlap with the sources, because the sources are placed in the center of each cell falling within the seismogenic zones, whereas, the observation points are placed at the corners of the grid, and inside the structural polygons of Fig. 3.

The synthetic signals are computed for frequencies up to 1 Hz. Depending upon the magnitude the hypo-central depth is not considered as constant parameter , it is taken as 10 km for sources with M <7:0, for sources with $7 \leq M < 8$ it is fixed to 15 km whereas it is fixed to 20 km for catastrophic earthquakes of $M \geq 8{:}0$ as in previous studies [47],[48],[49],[50],[51],[52],[53], [54]. This procedure is adopted to justify the relationship of magnitude-depth which is shown in the statistical parameters of the earthquake occurrences [e.g. [11]].To limit the number of synthetic seismograms to be computed, the maximum epicentral distance considered in the generation of the time series depends on the source magnitude: 150 km for $M < 6$, 200 km for $6 \leq M < 7$, 400 km for $7 \leq M < 8$ and 800 km for $M \geq 8$.After the seismicity, the source mechanisms, the structural models and the observation points are all defined, synthetic signals are computed. In the far field, i.e. roughly speaking for epicentral distances larger than the source depth, the modal summation technique [55, 56, 2,3] is used, as it is very efficient from the computational point of view. For paths, shorter than the hypocentral depth the discrete wavenumber technique is adopted [57], which gives the full wave field, including all body waves and near field, at the penalty of a longer computational time. At each site, the horizontal components (P - SV) radial and SH transverse syntheticseismograms are first computed for a seismic moment of $10^{-7} Nm$. The magnitude and the finiteness of thesource are accounted using the size and time scaled point source model [58] which is based on an extendedsource model provided by the PULSYN06 algorithm [59]. As shown by [2] site structural model is utilizedalong the complete path if source-site path goes across one or more boundaries amongst structural models,as the station records are generally more sensitive to the local structural environment. A vector sum isestimated after rotating the horizontal components into a reference system at each site that are mutual tothe entire region (N-S and E-W directions). Resulting from any adjacent source, signal of highest amplitudeis selected and associated to the specific site. We concentrate on D_{max}, V_{max} and *DGA* amongst the strong ground motion representativeparameters. 1 Hz upper limit of frequency is adequate as observed by the Fourier spectra of displacementand velocity to consider controlling role of seismic waves but the same is not true for acceleration [e.g. [48]].Then again, choice of higher frequency limit cannot be applied in computations as the necessary informationof seismic sources and as well as of lateral heterogeneity are normally not accessible for the size of theareas usually required in zoning. The present average design response spectra can be used for extendingthe deterministic modeling for frequencies >1*Hz* for the case of acceleration [48]. The DGA values are obtained by scaling the chosen normalized design response spectrum (normalized elastic acceleration spectraof the ground motion for 5 per cent critical damping) with the response spectrum computed at frequencies<1*Hz*. After the October 8, 2005 earthquake, the government of Pakistan realized that implementation of building code according to the international standards was an imperative to avoid such losses of human lives. To address this issue, a Pakistan specific standard building code was developed but not properly implemented. Therefore, the EC8 European code for soil A is used in this study. The choice of the soil A, i.e. stiff soil, is justified by the fact that in all the regional structural models of Fig. 4 the topmost S-wave velocity is greater than 0.8 km/sec.

Seismic Hazard Maps

The spatial distribution of *DGA*, $V_{max}$and D_{max}obtained from the entire synthetic seismograms arecomputed as discussed in Section 3 has been mapped and presented in Figs 10-11, respectively.In terms of DGA, the most severe hazard is found in the epicentral zone of the great Muzaffarabad earthquake of M 7.6 , 2005 (Fig. 8) and its adjacent areas, where the DGA estimate is as high as 0.6 *g* – 1.20 g, and same value is observed in the epicentral zone of the September 24, 2013 Awaran district (Balochistan) earthquake, M 7.8, followed by its September 28, 2013, M 6.8 aftershock and the 1945 Makran coast earthquake, M above 8.0, occurred. It must be noted that the Gawadar, and Pasni ports are both included in the above-mentioned hazardous area.Islamabad, which is the capital city of Pakistan, has DGA estimate as high as 0.3 *g* – 0.6 *g*. Similarly, in the regions of Chaman fault, the epicentral zone of the Quetta earthquake of 1935, Suleiman ranges and upper Punjab have DGA values between 0.3 *g* –0.6 *g*. The northern areas of Pakistan have DGA values 0.15- 0.30 g, the DGA for Peshawar is 0.08-0.15 *g*.The areas of Sind, namely Hyderabad and Thatta, have DGA values 0.3 *g* –0.6 *g*. Lahore, the capital city of Punjab has DGA 0.15-0.30g, the same is observed in Balochistan plateau and in Karachi, the mega city of Pakistan. The Indus plain and the region of lower Punjab are characterized by DGA values in the range 0.04-0.08 *g*. Lower DGA is estimated for the region of Balochistan near Nokundi, in the range 0.02-0.04 *g*.

For displacement and velocities, the highest values are obtained in Muzaffarabad, Kashmir, Awaran, Makhran coast, Quetta and its surroundings with velocity and displacement in the range of 60–120 $cm\ s^{-1}$and 30–60 *cm*, respectively. In the other parts of the region, such as the capital of Pakistan Islamabad and its twin city Pindi, areas of Balochistan namely Khost, Surab, Pasni, and NWFP, Chitral, the maximum velocity is up to 30–60 $cm\ s^{-1}$ and the maximum displacement is 15–30 *cm*. In the area of lower Punjab, the maximum velocity and displacement are in the range 2–4 $cm\ s^{-1}$and 7–15 *cm*, respectively. The areas of Sind like Karachi, Khairpur, Sukkur, Thar desert have velocity in the range of 15-30 $cms^{-1}$and displacement in the range of 15- 30 *cm*.

CONCLUSION

By computing realistic synthetic seismograms, the deterministic seismic hazard map has been prepared for Pakistan and adjoining areas in terms of D_{max}, $V_{max}$and DGA values.The seismic hazard is found to be highest in

Muzaffarabad, as the seismic hazard is controlled by the largest event in the area. The DGA value for this region is found to be 0.6 *g* – 1.20*g*. In the other regions of high seismicity, such as Islamabad, capital of Pakistan and Quetta, estimates of DGA values are as high as 0.30– .60*g*. The peak velocity and displacement are also high in these earthquake-prone zones. The ground shaking values are definitely high for the existing infrastructure and could result in great damage and huge socio-economic losses due to the high economic importance of the areas.

The neo-deterministic modelling of seismic hazard for the Pakistan and adjoining regions yields meaningful results and gives us a reasonable and economically logical scientific means for seismic zonation and hazard assessment. The main benefit of the approach lies in its capacity to directly evaluate the outcomes of source mechanics and wave propagation, while local site effects are roughly considered when using the design spectra to obtain the DGA from the synthetic response spectra. The expected PGA and computed DGA for a few strong earthquakes in Pakistan is shown in Table 1. We believe that the research and data we submit here will enrich the understanding of the seismic hazard in Pakistan and adjoining regions. Moreover, our research may help those civil and earthquake engineers who desire to launch thorough and detailed studies of earthquake hazard.

REFERENCES

1. Zaré, M., &Karmimi-Paridari, S. (2008). Balakot, Muzaffarabad Earthquake of 8 October 2005, Mw 7.6; Field Observations on Geological Aspects. In The 14th World Conference on Earthquake Engineering, Beijing, China. Retrieved from http://www. iitk. ac. in/nicee/wcee/article/14_01-1044.
2. Panza, G. F., Romanelli, F., & Vaccari, F. (2001). Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to seismic zonation. In Advances in geophysics (Vol. 43, pp. 1-95). Elsevier.
3. Panza, G. F., La Mura, C., Peresan, A., Romanelli, F., & Vaccari, F. (2012). Seismic hazard scenarios as preventive tools for a disaster resilient society. In Advances in geophysics(Vol. 53, pp. 93-165). Elsevier.
4. Sarwar, F.(2015). Seismic activities and its time prediction modelling: Ph.D. thesis of Farhana Sarwar(unpublished). Submitted to University of Balochistan, Quetta Pakistan.
5. Keilis-Borok, V., & Soloviev, A. A. (Eds.). (2013). Nonlinear dynamics of the lithosphere and earthquake prediction. Springer Science & Business Media.
6. Peresan, A., Kossobokov, V., Romashkova, L., &Panza, G. F. (2005). Intermediate-term middle-range earthquake predictions in Italy: a review. Earth-Science Reviews, 69(1-2), 97-132.
7. Peresan, A., Zuccolo, E., Vaccari, F., Gorshkov, A., &Panza, G. F. (2011). Neo-deterministic seismic hazard and pattern recognition techniques: time-dependent scenarios for North-Eastern Italy. Pure and Applied Geophysics, 168(3-4), 583-607.
8. http:// www.ezilon.com/maps/asia/pakistan-physical-maps.html. [Online].
9. Gupta, I. D. (2002). The state of the art in seismic hazard analysis. ISET Journal of Earthquake Technology, 39(4), 311-346.
10. Reiter, L. (1991). Earthquake hazard analysis: issues and insights. Columbia University Press.
11. Molchan, G., Kronrod, T., &Panza, G. F. (1997). Multi-scale seismicity model for seismic risk. Bulletin of the Seismological Society of America, 87(5), 1220-1229.
12. Vaccari, F., Tadili, B., El Qadi, A., Ramdani, M., Brahim, L. A., &Limouri, M. (2001). Deterministic seismic hazard assessment for North Morocco. Journal of Seismology and Earthquake Engineering, 3(1), 1-12
13. Peresan, A., Zuccolo, E., Vaccari, F., Gorshkov, A., &Panza, G. F. (2011). Neo-deterministic seismic hazard and pattern recognition techniques: time-dependent scenarios for North-Eastern Italy. Pure and Applied Geophysics, 168(3-4), 583-607.
14. Monalisa, Khwaja, A. A., & Jan, M. Q. (2007). Seismic hazard assessment of the NW Himalayan fold-and-thrust belt, Pakistan, using probabilistic approach. Journal of Earthquake Engineering, 11(2), 257-301.
15. Nespak National Engineering Services of Pakistan. (2007). Building Code of Pakistan Seismic Hazard Evaluation Studies", Ministry of Housing and Works, Government of Pakistan.

16. Panza, G. F., Romanelli, F., Vaccari, F., Decanini, L., &Mollaioli, F. (1999). Contribution of the deterministic approach to the characterization of seismic input (No. IC--99/149). Abdus Salam International Centre for Theoretical Physics.
17. Costa, G., Panza, G. F., Suhadolc, P., & Vaccari, F. (1993). Zoning of the Italian territory in terms of expected peak ground acceleration derived from complete synthetic seismograms. Journal of applied geophysics, 30(1-2), 149-160.
18. Parvez, I. A., Vaccari, F., &Panza, G. F. (2003). A deterministic seismic hazard map of India and adjacent areas. Geophysical Journal International, 155(2), 489-508.
19. Meltzer, A., Sarker, G., Beaudoin, B., Seeber, L., & Armbruster, J. (2001). Seismic characterization of an active metamorphic massif, Nanga Parbat, Pakistan Himalaya. Geology, 29(7), 651-654.
20. Roecker, S. W. (1982). Velocity structure of the Pamir-Hindu Kush Region: Possible evidence of subducted crust. Journal of Geophysical Research: Solid Earth, 87(B2), 945-959.
21. Johnson, M., & Vincent, C. (2002). Development and testing of a 3D velocity model for improved event location: A case study for the India-Pakistan region. Bulletin of the Seismological Society of America, 92(8), 2893-2910.
22. Roecker, S. W., Sabitova, T. M., Vinnik, L. P., Burmakov, Y. A., Golvanov, M. I., Mamatkanova, R., &Munirova, L. (1993). Three-dimensional elastic wave velocity structure of the western and central Tien Shan. Journal of Geophysical Research: Solid Earth, 98(B9), 15779-15795.
23. Pegler, G., & Das, S. (1998). An enhanced image of the Pamir–Hindu Kush seismic zone from relocated earthquake hypocentres. Geophysical Journal International, 134(2), 573-595.
24. Chatelain, J. L., Roecker, S. W., Hatzfeld, D., & Molnar, P. (1980). Microearthquake seismicity and fault plane solutions in the Hindu Kush region and their tectonic implications. Journal of Geophysical Research: Solid Earth, 85(B3), 1365-1387.
25. Zeitler, P. K., Koons, P. O., Bishop, M. P., Chamberlain, C. P., Craw, D., Edwards, M. A., ... & Kidd, W. S. (2001). Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion. Tectonics, 20(5), 712-728.
26. Reiter, D., Rodi, W., & Johnson, M. (2005). Development of a tomographic upper-mantle velocity model beneath Pakistan and northern India for improved regional seismic-event location. Bulletin of the Seismological Society of America, 95(3), 926-940.
27. Vinnik, L., Singh, A., Kiselev, S., & Kumar, M. R. (2007). Upper mantle beneath foothills of the western Himalaya: subducted lithospheric slab or a keel of the Indian shield?. Geophysical Journal International, 171(3), 1162-1171.
28. Billington, S., Isacks, B. L., &Barazangi, M. (1977). Spatial distribution and focal mechanisms of mantle earthquakes in the Hindu Kush–Pamir region: a contorted Benioff zone. Geology, 5(11), 699-704.
29. Sarwar, F., Iqbal, S., & Kamal, S. (2011). An analysis of Pakistan's local network catalog of earthquake for the period of 1905–2007. Sci Int, 23(1), 13-18.
30. http://asc-india.org/menu/gquakes.htm.. [Online].
31. Bilham, R. (2004). Historical studies of earthquakes in India. Ann. Geophys, 47(2), 839-858.
32. Aoudia, A., Vaccari, F., Suhadolc, P., &Meghraoui, M. (2000). Seismogenic potential and earthquake hazard assessment in the Tell Atlas of Algeria. Journal of Seismology, 4(1), 79-98.
33. Panza, G.F., Irikura, K., Kouteva, M., Peresan, A., Wang, Z., &Saragoni, R. (2011). Advanced seismic hazard assessment, Pageoph Topical Volume. ISBN 978-3-0348-0039-6 and ISBN: 978-3-0348-0091-4.
34. Gelfand, I. M., Guberman, S. I., Izvekova, M. L., Keilis-Borok, V. I., &Ranzman, E. J. (1972). Criteria of high seismicity, determined by pattern recognition. In Developments in Geotectonics (Vol. 4, pp. 415-422). Elsevier.
35. Sarwar, F., Iqbal, S., Qaisar, M., Rehman, A., Akhtar, F., & Raza, S. M. (2016). Earthquake Statistics and Earthquake Research Studies in Pakistan. Open Journal of Earthquake Research, 5(02), 97.
36. Khattri, K. N., Rogers, A. M., Perkins, D. M., &Algermissen, S. T. (1984). A seismic hazard map of India and adjacent areas. Tectonophysics, 108(1-2), 93-134.
37. Bhatia, S. C., Kumar, M. R., & Gupta, H. K. (1999). A probabilistic seismic hazard map of India and adjoining regions. Annals of Geophysics, 42(6).

38. Seeber, L., Armbruster, J. G., & Jacob, K. H. (1999). Probabilistic assessment of earthquake hazard for the state of Maharashtra. Report to Government of Maharashtra Earthquake Rehabilitation Cell, Mumbai.
39. Molnar, P., Fitch, T. J., & Wu, F. T. (1973). Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia. Earth and Planetary Science Letters, 19(2), 101-112.
40. Lisa, M., Khan, S. A., &Khwaja, A. A. (2004). Focal mechanism study of north Potwar deformed zone, Pakistan. Acta SeismologicaSinica, 17(3), 255-261
41. Verma, R. K., & Sekhar, C. C. (1986). Focal mechanism solutions and nature of plate movements in Pakistan. Journal of geodynamics, 5(3-4), 331-351.
42. Verma, R. K., Mukhopadhyay, M., &Bhanja, A. K. (1980). Seismotectonics of the Hindukush and Baluchistan arc. Tectonophysics, 66(4), 301-322.
43. Armbruster, J., Seeber, L., Quittmeyer, R., & Farah, A. (1980). Seismic network data from Quetta, Pakistan: The Chaman Fault and the fault related to the 30 May 1935 earthquake
44. Fitch, T. J. (1970). Earthquake mechanisms in the Himalayan, Burmese, and Andaman regions and continental tectonics in central Asia. Journal of Geophysical Research, 75(14), 2699-2709.
45. Chandra, U. (1978). Seismicity, earthquake mechanisms and tectonics along the Himalayan mountain range and vicinity. Physics of the Earth and Planetary Interiors, 16(2), 109-131.
46. Panza, G. F., Vaccari, F., &Cazzaro, R. (1999). Deterministic seismic hazard assessment. In Vrancea earthquakes: tectonics, hazard and risk mitigation (pp. 269-286). Springer, Dordrecht.
47. Orozova-Stanishkova, I. M., Costa, G., Vaccari, F., &Suhadolc, P. (1996). Estimates of 1 Hz maximum acceleration in Bulgaria for seismic risk reduction purposes. Tectonophysics, 258(1-4), 263-274.
48. Panza, G. F., Vaccari, F., Costa, G., Suhadolc, P., & Fah, D. (1996). Seismic input modelling for zoning and microzoning. Earthquake Spectra, 12(3), 529-566.
49. Alvarez, L., Vaccari, F., &Panza, G. F. (1999). Deterministic seismic zoning of eastern Cuba. pure and applied geophysics, 156(3), 469-486.
50. Bus, Z., Szeidovitz, G., & Vaccari, F. (2000). Synthetic seismogram based deterministic seismic zoning for the Hungarian part of the Pannonian basin. In Seismic Hazard of the Circum-Pannonian Region (pp. 205-220). Birkhäuser, Basel.
51. Markušić, S., Suhadolc, P., Herak, M., & Vaccari, F. (2000). A contribution to seismic hazard assessment in Croatia from deterministic modeling. In Seismic Hazard of the Circum-Pannonian Region (pp. 185-204). Birkhäuser Basel.
52. Radulian, M., Vaccari, F., Mandrescu, N., Panza, G. F., &Moldoveanu, C. L. (2000). Seismic hazard of Romania: deterministic approach. In Seismic Hazard of the Circum-Pannonian Region (pp. 221-247). Birkhäuser, Basel.
53. Živčić, M., Suhadolc, P., & Vaccari, F. (2000). Seismic zoning of Slovenia based on deterministic hazard computations. In Seismic Hazard of the Circum-Pannonian Region (pp. 171-184). Birkhäuser, Basel.
54. El-Sayed, A., Vaccari, F., &Panza, G. F. (2001). Deterministic seismic hazard in Egypt. Geophysical Journal International, 144(3), 555-567.
55. Panza, G. F., &Suhadolc, P. (1987). Complete strong motion synthetics. Seismic strong motion synthetics, 4, 153-204.
56. Florsch, N., Fäh, D., Suhadolc, P., &Panza, G. F. (1991). Complete synthetic seismograms for high-frequency multimodeSH-waves. Pure and Applied Geophysics, 136(4), 529-560.
57. Pavlov, V. M. (2009). Matrix impedance in the problem of the calculation of synthetic seismograms for a layered-homogeneous isotropic elastic medium. Izvestiya, Physics of the Solid Earth, 45(10), 850-860.
58. Parvez, I. A., Romanelli, F., &Panza, G. F. (2011). Long period ground motion at bedrock level in Delhi city from Himalayan earthquake scenarios. Pure and applied geophysics, 168(3-4), 409-477.
59. A. Gusev, Broadband kinematic stochastic simulation of an earthquake source: a refined procedure for application in seismic hazard studies," Pure Appl. Geophys , pp. 168, 155–200. doi: 10.1007/s00024-010-0156-3, 2011.

Fig.1 Geographical Map of Pakistan with Adjoining regions [8].

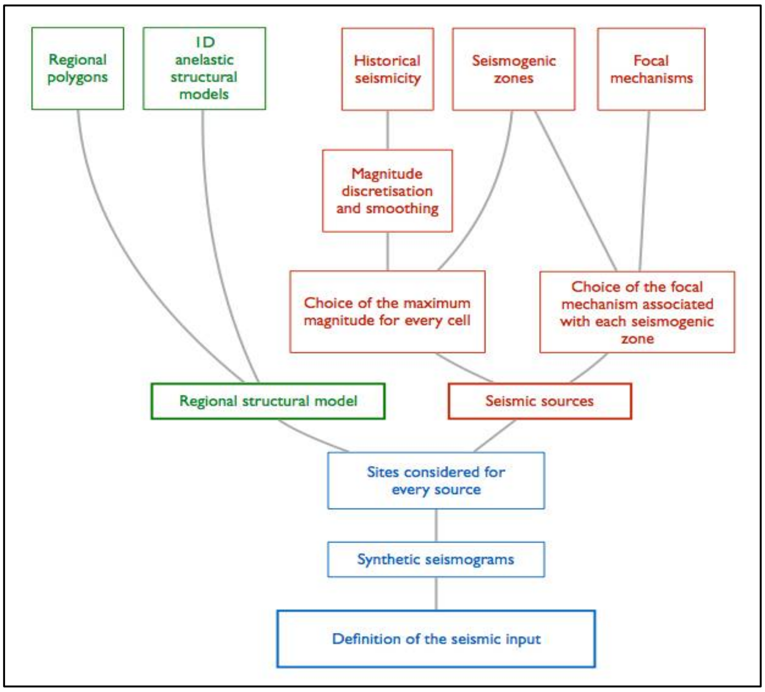

Fig. 2. The flow chart of the computation process.

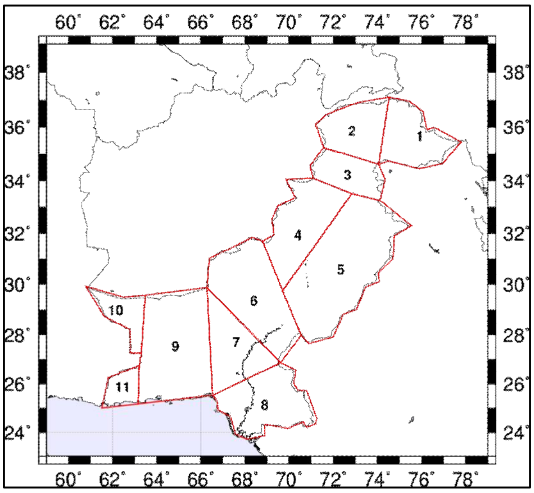

Fig. 3. Boundaries of regional structural polygons.

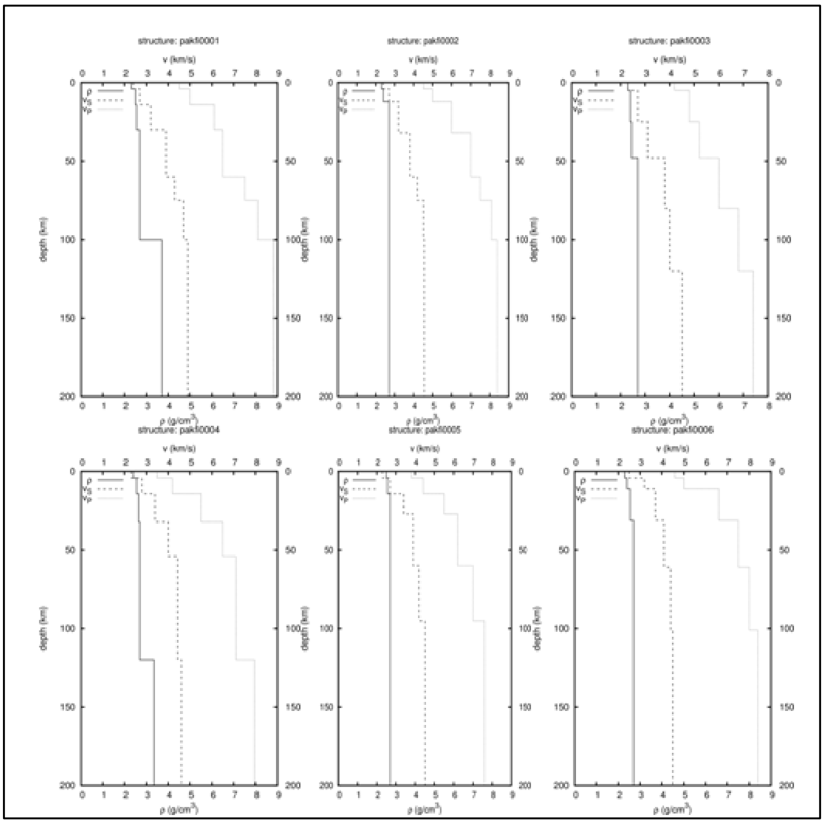

Fig. 4a. Layering of the regional structural models for polygons 1 to 6 of Fig. 2. The models continue to a depth of about 1000 km, but only the uppermost 200 km are shown here to better appreciate the details of crust and upper mantle properties.

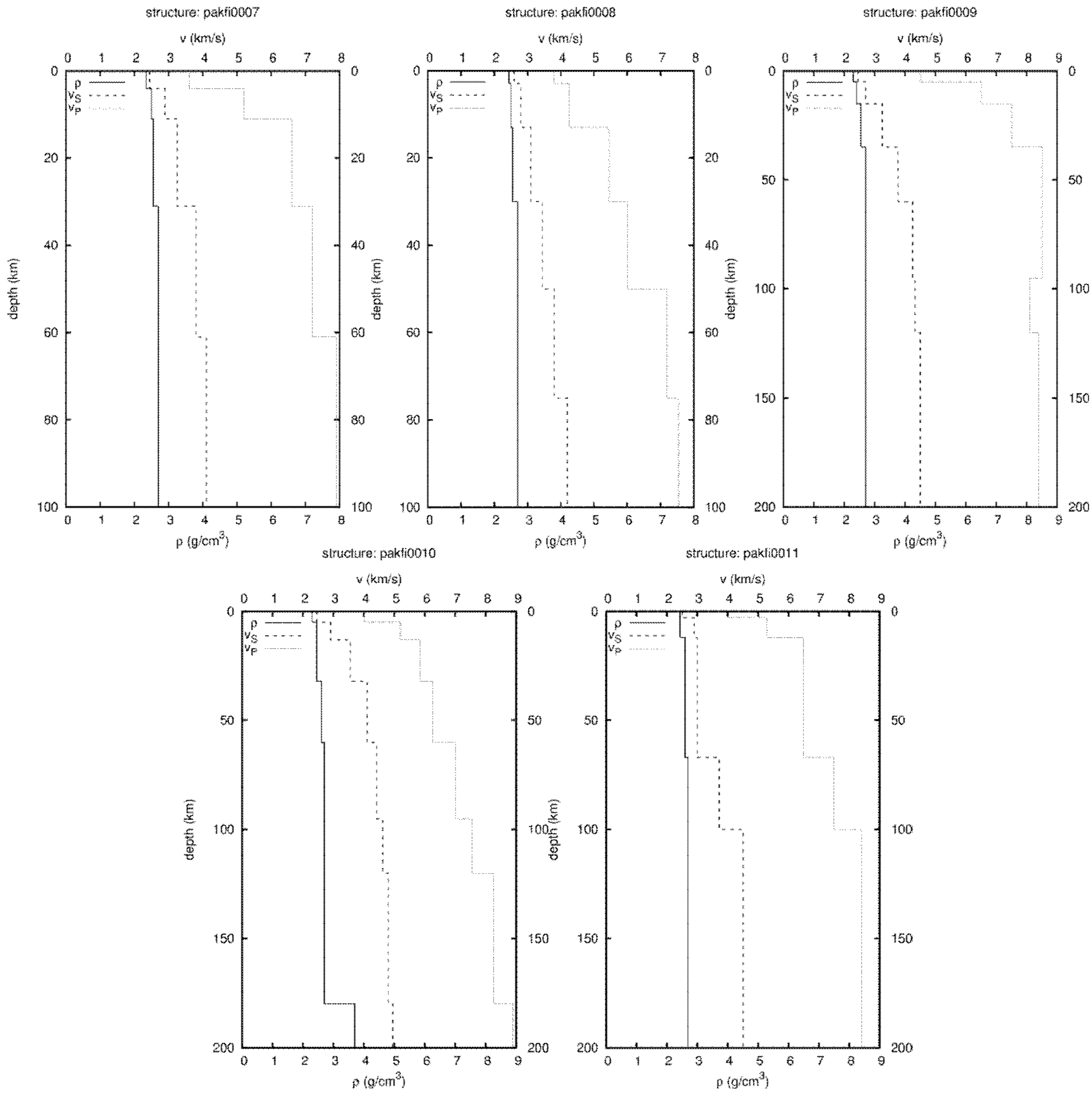

Fig. 4b. Same as Fig.3a for polygons 7 to 11 of Fig. 3.

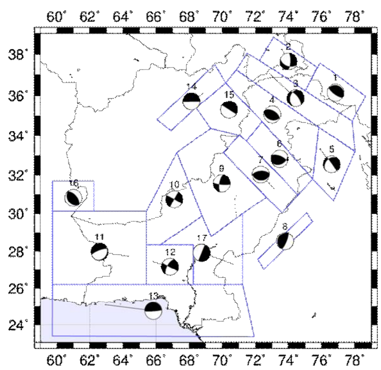

Fig. 5. Boundaries of the seismogenic zones, and the focal mechanism associated with the sources belonging to each seismogenic zone.

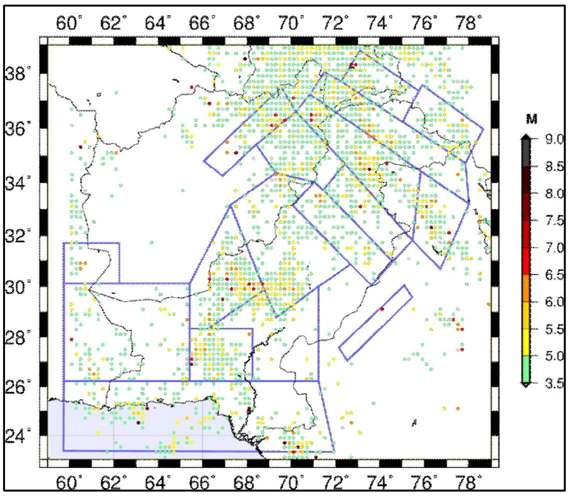

Fig. 6. Map of the observed seismicity, gridded into 0.2° x 0.2° cells.

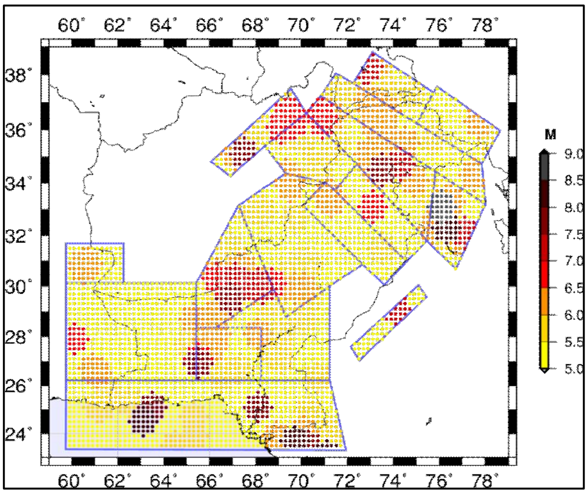

Fig. 7. Representation of the seismicity smoothed within the seismogenic zones.

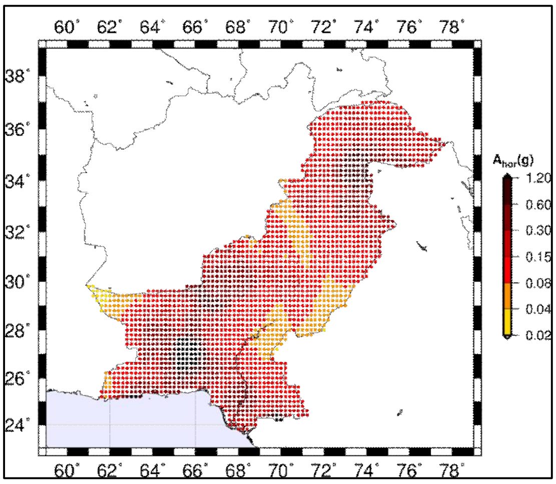

Fig. 8. Map showing the horizontal DGA values for the studied area.

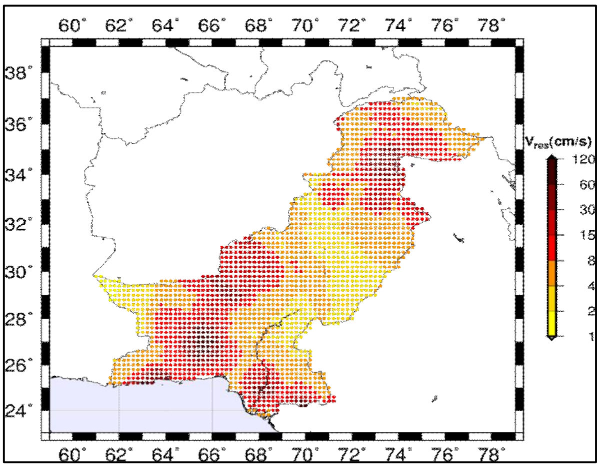

Fig. 9. Map of the maximum horizontal velocity for Pakistan.

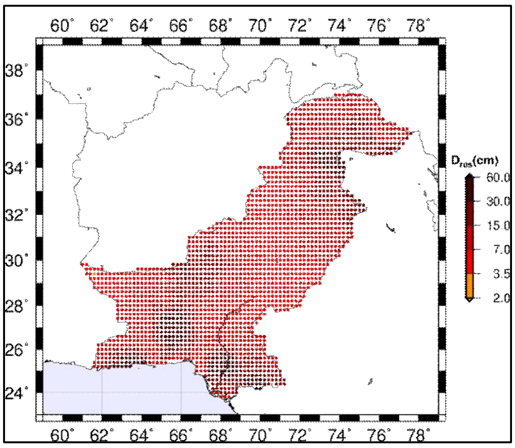

Fig. 10. Map of the maximum horizontal displacement for Pakistan.

Table 1. The expected PGA and computed DGA for a few strong earthquakes in Pakistan[4].

Longitude	Latitude	Region	PGA	DGA(g)	M	Date
73°30′E	33°40′N	Muzaffarabad	0.38	0.6 *g* – 1.20	8.0	8/10/2005
62°18′E	25°10′N	Gawadar	0.24	0.6 *g* – 1.20	7.6	1947
63°27′E	25°15′N	Pasni	0.32	0.6 *g* – 1.20	7.8	28/05/1945
72°90′E	35°10′N	Balakot Patan	0.26	0.3-0.6	6.2	28/12/1974
64°00′E	25°40′N	Makran	0.30	0.6 *g* – 1.20	7.7	1945
73°45′E	33°59′N	Bagh	0.42	0.3-0.6	7.6	8/10/2005